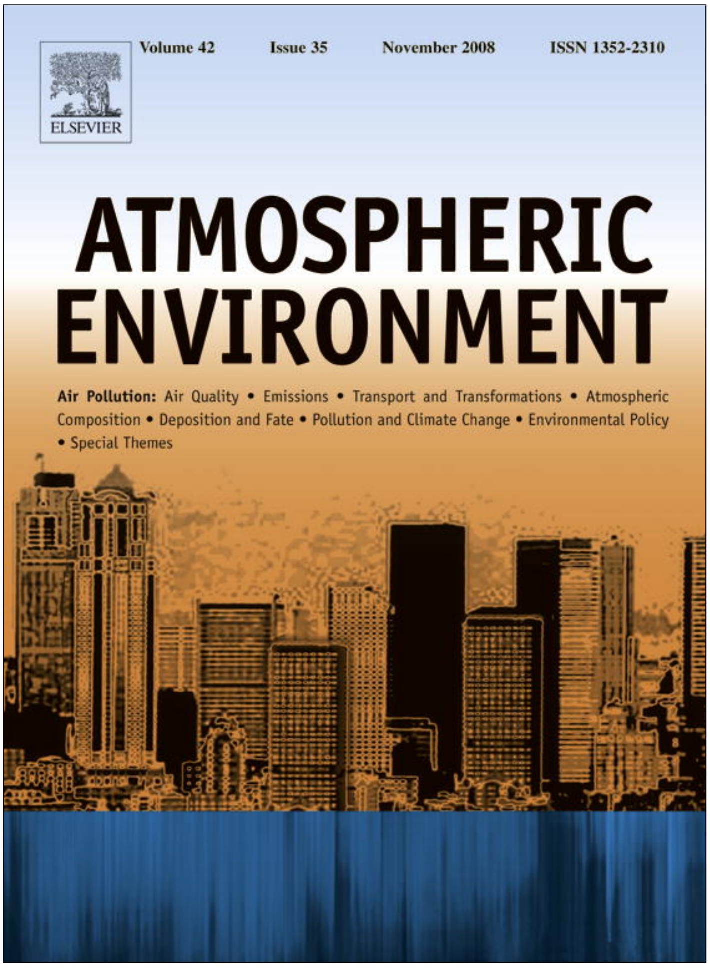
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The impact of a Bus Rapid Transit system on commuters' exposure to Benzene, CO, $PM_{2.5}$ and PM_{10} in Mexico City

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ABSTRACT

Carbon monoxide (CO), benzene and other volatile organic compounds (VOCs) and suspended particles $PM_{2.5}$ and PM_{10} were measured inside public transportation vehicles, before and after a new Bus Rapid Transit (BRT) system was implemented in Mexico City in June 2005. The objective was to evaluate the BRT system's impact on commuters' exposure to these air pollutants. The BRT system replaced conventional transport modes along 20 km of Insurgentes Avenue, and features confined corridors and new articulated diesel buses. We assessed the impact of the transportation mode on commuters' exposure using least squares regression models. We also analyzed the chemical composition of VOCs to evaluate the possible origin of these species. The implementation of the BRT system resulted in reductions in commuters' exposure to CO, benzene and $PM_{2.5}$ ranging between 20% and 70%. No significant reductions in PM_{10} exposure were observed. Lower commuting times further reduced total commuters' exposure. Major sources affecting VOCs inside all transport modes are likely to be related to traffic and to emissions from the use of Liquefied Petroleum Gas. The results suggest that BRT systems could in general be an effective means of reducing human exposure to traffic related air pollutants and associated health impacts.

1. Introduction

Cities around the world are grappling with the many consequences of rising motorization and traffic congestion. The negative effects of traffic include lost time and productivity, vehicular accidents, greenhouse gas emissions, deteriorating air quality and associated risks on respiratory and cardiovascular health, among others (Dahl, 2005; WHO and World Bank, 2004; WHO, 2005). In addition, many studies have shown that the air people breathe while in transportation is particularly unsafe due to the high concentrations of carbon monoxide (CO), suspended particles (PM_{10} and $PM_{2.5}$) and volatile organic compounds (VOCs), among others (Adams et al., 2001a; Georgoulis et al., 2002; Kuo et al., 2000). A suite of measures has been implemented to mitigate the externalities associated with traffic. A particularly important measure that combats many of the impacts of traffic is the provision of rapid and efficient public transport networks as an alternative to private cars. Bus Rapid Transit (BRT) systems have been identified as an inexpensive, efficient and increasingly popular public transportation option. In this study we explore how the implementation of a BRT system can actually improve the quality of the air people breathe while commuting.

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1.1. Previous studies on commuter's exposure

Commuters' exposure to air pollutants inside vehicles has been of special interest in many recent studies. With respect to CO, transport microenvironments have been identified as the most polluted spaces in comparison with other microenvironments (Georgoulis et al., 2002; Scotto di Marco et al., 2005). In the case of VOCs, transport microenvironments were also shown to be an important contributor to total exposure (Edwards et al., 2006; Saarela et al., 2003). For $PM_{2.5}$, Behrentz et al. (2005) have found that transport microenvironments significantly contribute with about 15% to total personal exposure. Rojas-Bracho et al. (2004) also found an average increase in personal $PM_{2.5}$ and PM_{10} exposures of 2.5 and 2.7 $\mu g\,m^{-3}$, respectively, for each hour that was spent in transportation.

The air pollution inside vehicles can originate from the infiltration of emissions of surrounding vehicles and/or from self-pollution, i.e. the vehicle's own emissions coming from fuel leaks and combustion byproducts entering the cabin through vents, doors and windows.

Various studies have analyzed exposures to air pollutants by comparing different transport modes. A common result for gaseous air pollutants and elemental carbon was that private and low-capacity public transport vehicles are among the microenvironments with the highest commuters' exposures, whereas lower levels of such pollutants have been found in high capacity public transport vehicles like buses and metro (Adams et al., 2002; Chan et al., 1999; Duffy and Nelson, 1997; Kaur et al., 2005a; Pang and Mu, 2007). For exposure to particulate matter, little or no differences have been found between on-road transport modes, although higher concentrations have been found in underground transport in certain cities (Adams et al., 2001a,b). A broader discussion on the results of these studies can be found in the recent review by Kaur et al. (2007).

In Mexico City, Fernández-Bremauntz and Ashmore (1995) measured CO concentrations in different transport modes and on different commuting routes during the winter of 1991. The highest concentrations were measured in private cars, followed by minibuses, buses, and subway. In 2002 and 2003, Gómez-Perales et al. (2004, 2007) conducted a comparable study, measuring benzene and $PM_{2.5}$ in addition to CO. For CO, the same commuters' exposure patterns in public transportation were found as in the previous study, but with greatly reduced absolute concentrations. This decline in CO levels observed in Mexico City is likely to be the result of various strategies introduced by the government to reduce air pollutant emissions, which include inspection and maintenance of vehicles and the introduction of cleaner vehicle technologies, such as three-way catalytic converters. Shiohara et al. (2005) measured different VOCs in commuter microenvironments finding the highest concentrations of benzene, toluene, ethylbenzene and *m*/*p*-xylene in private cars, followed by minibuses, buses and metro. The highest concentrations of formaldehyde, however, were found in minibuses.

1.2. Bus Rapid Transit (BRT) systems

Because of the high levels of air pollutants found in transportation modes and the often long commuting times, transport microenvironments are an important place to reduce air pollution concentrations in order to minimize overall population exposure. Many transportation measures exist that could lead to significant improvements in commuters' exposure by reducing both in-vehicle air pollution and commuting times. Among these measures, BRT systems are being implemented in cities around the world as an efficient, sustainable, and low-cost alternative to conventional public transport. BRT systems provide a more rapid, metro-like service to commuters by including such features as separated busways, high capacity vehicles, fixed stations and off-bus fare collection. Such improvements to city's bus systems can potentially lead to significant environmental benefits by reducing the number of vehicles on the road, controlling the number of high-polluting starts and stops and replacing old buses with new generation public transport vehicles with improved technologies (Wright, 2003). Especially in the rapidly growing cities of developing countries (e.g. Bogotá, Colombia; Jakarta, Indonesia; and Beijing, China), BRT systems have been recognized as a low cost solution to increasing traffic problems.

In Mexico City, a BRT system called "Metrobus" was implemented in June, 2005 along 20 km of Insurgentes Avenue, which is one of Mexico City's principal north-south arterial routes. Insurgentes Avenue has a total length of 29 km and traverses industrial (Northern part), residential (Southern part) and commercial areas. 262 minibuses (with a capacity of about 35 passengers each, 20–22 seats and the rest standing) and 90 buses (capacity: 88 passengers) were replaced by 98 articulated high capacity buses (capacity: 160 passengers) with modern and certified diesel engine technology which travel on separate bus lanes (Fig. 1a–c), to satisfy a demand of 250 900 passenger trips per day (SETRAVI, 2004; Metrobus, 2007).

Minibuses are one of the most prevalent public transportation modes in Mexico City, where they have long been recognized as a highly polluting transport option due to the age of the fleet (most of the units are more than six years old), the lack of a catalyst and poor maintenance. Furthermore, minibuses pick up passengers on demand at any point along the street, instead of using designated bus stops, thereby disrupting traffic flow, which results in higher per-vehicle emissions due to the frequent stops and starts. In 2004, 61% of all minibuses in Mexico City used gasoline, 35% used Liquefied Petroleum Gas (LPG), and the remaining vehicles used natural gas or diesel, with an increasing tendency towards LPG driven minibuses (GDF-SMA, 2006). Buses, which use diesel, have an average fleet age of 8.3 years (SETRAVI, 2004).

Therefore, the introduction of Mexico City's first BRT route was intended not only to fulfill the need of a more efficient public transport system, but also to improve both the quality of the environment and of commuters' life (Metrobus, 2007).

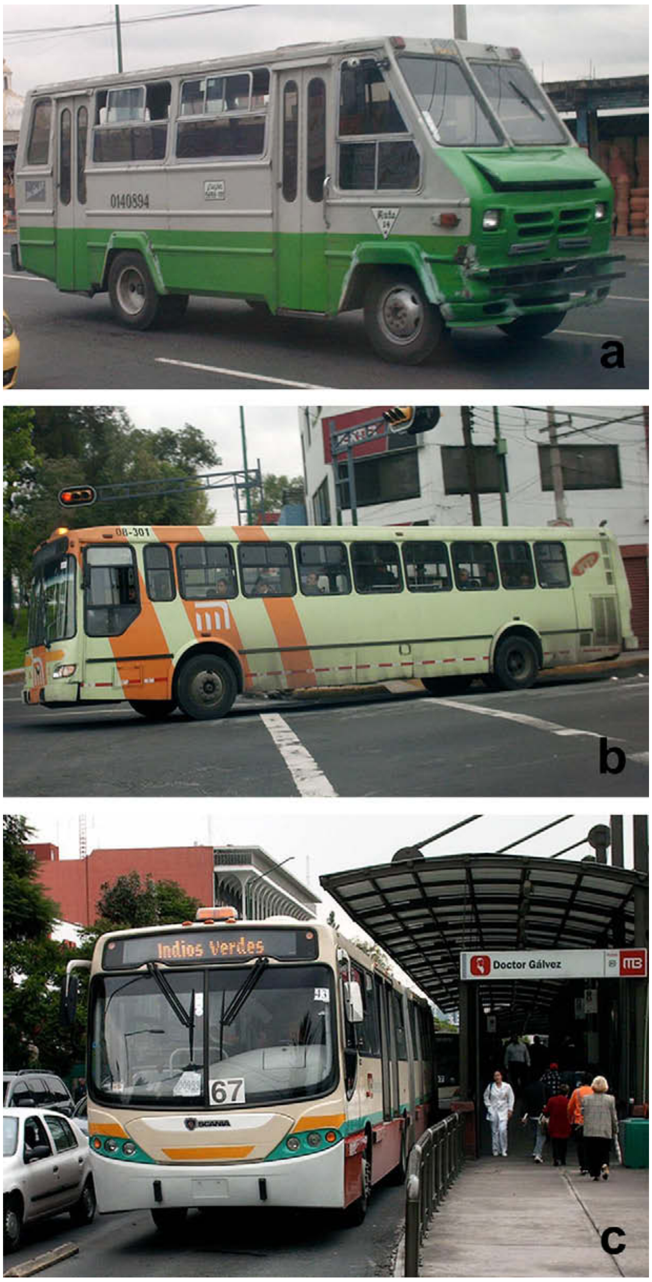

Fig. 1. Public transport vehicles in Mexico City: (a) minibus, (b) bus and (c) Metrobus on Insurgentes Avenue.

1.3. Rationale of this study

Commuters' exposure in transport microenvironments can be a sensitive indicator to evaluate the environmental benefits of the implementation of more efficient public transport systems using cleaner technologies. Exposures can be significantly reduced by the introduction of catalytic converters (Gómez-Perales et al., 2004, 2007), retrofitted buses (Hill et al., 2005), or the use of priority lanes for public transport (Flachsbart, 1989). However, to our knowledge, the potential benefit of a BRT system on commuters' exposure to air pollutants has never before been evaluated.

The objective of this study was to determine the impact of the recently implemented BRT system in Mexico City on commuters' exposure to air pollutants and commuting time. Furthermore, we analyzed the chemical composition of VOCs to assess the origin of commuters' exposures to these air pollutants.

2. Methods

2.1. Experimental design

From May to August of 2004, commuters' exposures to CO, ten speciated VOCs (propane, acetylene, pentane, hexane, heptane, benzene, octane, toluene, nonane and *o*-xylene), $PM_{2.5}$ and PM_{10}, were measured inside conventional minibuses and buses during the morning rush hour along Insurgentes Avenue in Mexico City.

From August to October of 2005, after the substitution of the conventional transportation modes by the Metrobus BRT system, commuters' exposures to these air pollutants were measured in the BRT vehicles traveling on the same route.

Trained technicians commuted in the vehicles using equipment to measure commuters' exposures to the above mentioned pollutants. Measurements were conducted in up to three vehicles simultaneously from Monday to Friday during the morning rush hour (7:30–9:00 AM), commuting from the Indios Verdes bus terminal in the Northern part of Mexico City to the San Ángel bus terminal in the Southern area of the city ($\sim$20 km). A total of 83 commuting trips were completed in 2004 and 68 commuting trips were carried out in 2005. The measured vehicle population was made up of 28 minibuses and 37 buses during the first measurement campaign, and 44 articulated Metrobuses during the second measurement campaign, identified by their license plates.

All monitors began to sample at the moment when the respective vehicle departed from the Indios Verdes terminal, with their intakes being held close to the technicians' breathing area. During the trip, the technicians registered the time of start and end, and recorded occasional problems with the equipment and special events (traffic jams, smokers inside the vehicle, etc.). Monitors were turned off shortly before arriving at the San Ángel bus terminal.

Commuters' exposures to CO were also simultaneously measured inside a private car on several days (Nissan Pickup, 1999 model).

2.2. Equipment, laboratory analysis, and QA/QC

CO was logged in 10 s intervals using Langan Model T15 personal exposure monitors. The monitors were calibrated before every monitoring week using a dynamic dilution calibrator with a zero air generator (API, models 700 and 701) at the National Center of Environmental Research and Training (CENICA) in Mexico City. Data were invalidated when the measurement covered less than 75% of total commuting time, due to a malfunctioning of the Langan monitors.

VOCs were collected in SUMMA stainless steel canisters equipped with a flow controller, allowing a constant sample flow from the beginning to the end of the commuting trip.

From these air samples, ten selected VOCs were analyzed in a GC-FID, according to EPA's method TO-14A (US-EPA, 1999). The VOCs were identified by using a ten times dilution mixture of a gas calibration standard (SAAN Co., containing 1 ppmv of each of the ten target species). A few samples were invalidated when the valve of the canister was found to be improperly closed at the end of the commuting trip or when the canister valve was left closed unintentionally at the beginning of the trip.

$PM_{2.5}$ and PM_{10} samples were collected with portable SKC sampling pumps with size selective impactors, using 37 mm Teflon® filters (Pall PTFE with support ring) and quartz fiber filters (Whatman QM-A). Sampling flows were adjusted to $4\,L\,min^{-1}$ before each sampling period and measured again after sampling concluded, with a maximum observed change of 5% with respect to the initial flow. Filters were weighed before and after sampling with a Cahn model C-35 analytic balance at CENICA, according to a Mexican Entity of Accreditation's (EMA) procedure. Samples were invalidated when the measurement covered less than 75% of total commuting time. 52 field blanks (21% of all valid samples) were obtained, and their average gravimetric weight was subtracted from sample filter weights to account for filter handling.

For all measured pollutants, and for the sake of quality control, duplicate measurements were obtained, collocating two identical samplers next to each other during several commuting trips. Precision for each monitoring method was determined as the mean of the percent differences between the respective duplicate measurements. The resulting precisions were 10.1% for CO ($n = 46$), 15.7% for benzene ($n = 26$), 30.5% for $PM_{2.5}$ ($n = 38$), and 33.7% for PM_{10} ($n = 30$).[1]

2.3. Fixed site monitoring (FSM) data

Ambient air pollutant concentrations were obtained from FSM stations from Mexico City's Automatic Air Quality Monitoring Network (SIMAT, 2006). From 36 FSM stations in the network, eight were selected as they were located less than 4 km from the commuting route and correlated against each other. Thus, the most representative FSM stations for ambient concentrations of each pollutant were identified and selected for further analysis along the commuting route. FSM CO data was obtained from Metro Insurgentes station (adjacent to the commuting route). $PM_{2.5}$, PM_{10}, and meteorological parameters were obtained from the Merced station (about 3.5 km away from Insurgentes Avenue). Data from the FSM stations were analyzed between 6AM and 9AM, coinciding with the commuting trips.

2.4. Data analysis

Descriptive statistics were calculated on the whole data set, invalidating samples that were collected in two occasions when the minibus driver was observed to smoke during the commuting trip. Most of the data distributions were non-normal; however, since the coefficient of variation was always smaller than 1.2, mean values and standard deviations will be used in this discussion (Gilbert, 1987).

For univariate hypothesis testing, the Wilcoxon and *t*-tests were used for normally and non-normally distributed samples, respectively.

Least squares regression models were run to assess the influence of covariates on commuters' exposures. Commuters' exposures to CO, benzene, $PM_{2.5}$ and PM_{10} were used as dependent variables, and ambient CO, $PM_{2.5}$ and PM_{10} concentrations, wind speed, relative humidity and temperature data collected at FSM stations were included as independent variables in the regression models. The meteorological parameters were included since the measurements were not performed in the same month of the year (although both were during the rainy season). Since part of each monitoring period coincided with summer vacations, a dummy variable was included in the model to control for potential traffic differences. Finally, the transport mode was included as a dummy variable for modeling the effect of minibus, bus and Metrobus on commuters' exposures. The Metrobus was modeled as the reference category. Variables that significantly influenced commuters' exposures were selected by stepwise elimination of variables.

Additional data were invalidated for the regression model when their representativity was in doubt. For instance, extreme CO concentrations were observed inside one minibus in particular. Also, only minibuses using LPG were included in the statistical analysis ($n = 38$), and those using gasoline ($n = 6$) were excluded given the small sample size. Data analysis in this section was carried out using the R statistical software package version 2.0.0 (R Development Core Team, 2004).

3. Results and discussion

3.1. Commuters' exposure concentrations and commuting times

Descriptive statistics of commuters' exposures to CO, benzene, $PM_{2.5}$ and PM_{10}, and commuting times in all public transport modes included in this study are presented in Table 1 and Fig. 2.

In 2004, CO average commuters' exposures in minibuses and buses were of 20.3 ± 11.9 ppmv and 11.5 ± 1.6 ppmv, respectively. These values are comparable to those reported in previous studies conducted in Mexico City (Gómez-Perales et al., 2004, 2007), but considerably higher than for other urban regions (Chan et al., 1999; Kaur et al., 2005a). In 2005, commuters' exposures in Metrobus were much lower (7.8 ± 1.4 ppmv, $p < 0.001$). Occasionally very high CO concentrations were recorded in minibuses, but not in buses or Metrobuses. The three maximum values (39.4, 41.4 and 75.3 ppmv), which appear as outliers in the boxplot of Fig. 2, were measured in the same minibus, indicating high self-pollution, probably due to poor maintenance of this vehicle in particular. These extreme concentrations exceed the WHO guideline value of 25 ppmv for one hour (WHO,

[1] The low precision for particle measurements can be attributed to a highly heterogeneous spatial distribution of particles inside the vehicle, and a high uncertainty due to filter handling relative to the collected mass.

Table 1
Commuters' exposure to CO, benzene, $PM_{2.5}$, and PM_{10} in the different public transport modes, compared to measurements at fixed site monitoring stations

	CO (ppmv)			Benzene (ppbv)			$PM_{2.5}$ ($\mu g\,m^{-3}$)			PM_{10} ($\mu g\,m^{-3}$)			FSM CO (ppmv)		FSM $PM_{2.5}$ ($\mu g\,m^{-3}$)		FSM PM_{10} ($\mu g\,m^{-3}$)		FSM WS ($m\,s^{-1}$)		FSM T (°C)		FSM RH (%)	
	M	B	MB	M	B	MB	M	B	MB	M	B	MB	2004	2005	2004	2005	2004	2005	2004	2005	2004	2005	2004	2005
n	37	40	51	27	29	54	33	37	51	34	34	57	30	35	30	31	24	28	30	35	30	35	30	34
Min	10.7	8.7	5.7	6.5	5.7	0.2	26	36	26	90	84	19	1.4	1.5	7	10	13	18	0.2	0.6	11.8	10.5	66.0	63.7
Median	15.8	11.4	7.6	13.6	10.3	4.2	130	128	99	193	202	183	2.9	2.1	30	23	58	42	0.9	1.4	14.9	14.9	74.0	78.7
Mean	20.3	11.5	7.8	18.2	10.4	4.0	155	146	112	201	212	188	2.9	2.3	29	24	52	44	0.9	1.6	14.5	14.9	74.4	79.1
Max	75.3	14.7	11.0	68.8	19.2	11.3	351	330	238	368	444	456	4.5	4.3	51	41	101	72	1.9	4.3	16.9	18.4	88.0	96.0
SD	11.9	1.6	1.4	13.2	3.0	2.0	81	81	51	67	88	87	0.7	0.6	11	8	20	14	0.4	0.8	1.3	1.6	5.2	9.2

Concentrations of CO, $PM_{2.5}$, and PM_{10} at FSM stations, measured simultaneously with the commuting trips.
FSM = Fixed site monitoring, WS = wind speed, T = temperature, RH = relative humidity, M = Minibus (2004), B = Bus (2004), MB = Metrobus (2005), SD = standard deviation.

2000). The average CO concentration in the minibuses stated above, however, complied with the WHO standard.

CO average concentrations monitored in the private car were 15.3 ± 3.4 ppmv in 2004 ($n = 18$), and 16.3 ± 3.2 ppmv in 2005 ($n = 5$). Although these values might not be representative of the vehicular fleet circulating in the city, they indicate that car drivers may be exposed to similar concentrations as commuters in minibuses. Apart from self-pollution, the surrounding vehicular emissions could be the main cause of high commuters' exposure to CO in private cars, given their lower intake height (Fernández-Bremauntz and Ashmore, 1995).

Benzene average concentrations measured in minibuses and buses during 2004 (18.2 ± 13.2 ppbv and 10.4 ± 3.0 ppbv, respectively) were within the range of results found in other commuter studies conducted in Mexico City (Gómez-Perales et al., 2004, 2007; Shiohara et al., 2005) and in other locations (Kuo et al., 2000). Again, concentrations in Metrobus were lower (4.0 ± 2.0 ppbv, $p < 0.001$). Very high individual benzene concentrations of up to 68.8 ppbv were measured in several LPG powered minibuses. These extreme concentrations were not related to the high CO concentrations discussed above, and are therefore likely to be caused by different factors. Whereas CO may come both from self-pollution and surrounding vehicles, benzene is unlikely to be emitted from a minibus, since most of these vehicles run on LPG. Therefore, the high benzene concentrations recorded in several minibuses most likely resulted from the penetration of exhaust emissions from surrounding vehicles.

A recent study on VOCs exposure in Mexico City (Serrano-Trespalacios et al., 2004) found a mean daily personal exposure to benzene of 5.7 ± 5.9 ppbv. Indoor and ambient levels of benzene were recorded at approximately half that value, leading the authors to conclude that differences between personal, indoor and ambient levels of benzene were a function of people being closer to vehicular sources. The present study confirms those conclusions, finding benzene concentrations in buses and minibuses to be 3.5 and 6 times higher than those recorded by Serrano-Trespalacios et al. (2004) for indoor and outdoor levels. According to the WHO (2000), no safe level of exposure to benzene can be recommended, and the European Community (EC, 2000) sets its annual guideline value to 5 $\mu g\,m^{-3}$ (1.5 ppbv), approximately half the level people are exposed to in Mexico City. Assuming the results of Serrano-Trespalacios et al. (2004) are similar to personal exposures of Metrobus riders, and that people spend approximately 2.5 h commuting each day, the Metrobus system could reduce total daily exposures to benzene by about 30% when compared to minibuses.

With respect to $PM_{2.5}$ and PM_{10}, average concentrations in transport microenvironments were between 3 to 5 times of those reported by FSM stations (Table 1), and also much higher than measurements of particulate matter reported in other studies (Adams et al., 2001a; Gulliver and Briggs, 2004). Although there are no guidelines for short-term exposures, it has been suggested that peak exposures do have a significant effect on human health (Michaels, 1996; Michaels and Kleinman, 2000).

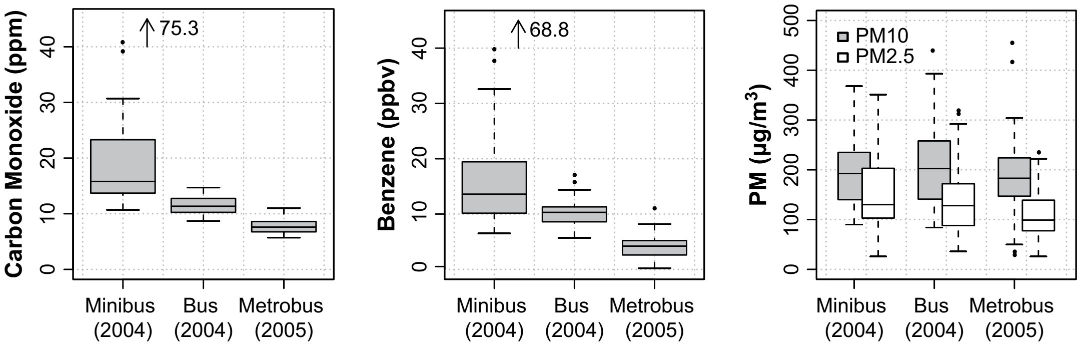

Fig. 2. Commuters' exposure to CO (in ppmv) , benzene (in ppbv) and particulate matter $PM_{2.5}$ and PM_{10} (in $\mu g\,m^{-3}$) by transport mode. The boxes indicate 25% quartile, median and 75% quartile, and the whiskers extend to the most extreme data point which is no more than 1.5 times the interquartile range from the box.

Average commuting time on the route dropped from 72 ± 11 min in minibuses and 76 ± 13 min in autobuses to 58 ± 3 min in Metrobuses ($p < 0.001$). Reductions in travel time not only provide more spare time each day to the users of public transport, but it also reduces their total exposure to pollutants, assuming that they are not spending extra time in microenvironments that have higher pollutant concentrations. In addition, commuting times for the implemented BRT system have become more predictable, since the standard deviation of commuting time was drastically lower in the Metrobus than in the conventional transport modes. These results refer to commuting trips between the two endpoints of the route during the morning rush hour, and may differ from trips at other times of the day.

3.2. Determinants of commuters' exposure

In this section, we used least squares regression models to show how much of the above described reductions in commuters' exposures to CO, benzene, $PM_{2.5}$ and PM_{10} may be associated with the implementation of the Metrobus (Models 1–4 in Table 2). In particular, we controlled for variations in ambient air pollution and meteorological conditions that also may have influenced personal exposure (see also Table 1).

Statistically significant covariates modeled as predictors of commuters' exposure were ambient concentrations, wind speed and ambient temperature. It is important to mention that all ambient pollutant concentrations decreased significantly from 2004 to 2005 ($p < 0.05$), possibly a result of significantly increased wind speed ($p < 0.001$).

Model 1 shows that transport mode and ambient CO concentrations explain 64% of CO commuters' exposures' total variability. The regression coefficients indicate that the implementation of the Metrobus system resulted in a reduction in CO exposures on average of 9.1 ppmv (45%) and 2.9 ppmv (25%) when compared to minibuses and autobuses, respectively.

The model for commuters' exposure to benzene showed that 37% of total variability can be explained by transport mode and ambient CO concentrations (as a proxy in the absence of ambient benzene data). Controlling for these independent variables, the implementation of the Metrobus system resulted in a reduction of average commuters' exposure to benzene of 13.2 ppbv (69%) and 6.0 ppbv (54%) relative to minibuses and buses, respectively.

For commuters' $PM_{2.5}$ exposure, transport mode and ambient $PM_{2.5}$ concentrations explained about 11% of the variability. Controlling for these independent variables, the implementation of the Metrobus system led to an average reduction in commuters' exposures to $PM_{2.5}$ of $46.9\,\mu g\,m^{-3}$ (30%) and $29.5\,\mu g\,m^{-3}$ (20%) relative to minibuses and buses, respectively.

In turn, for PM_{10}, ambient levels, wind speed and temperature explained less than 10% of the variability of commuters' exposures, and transport mode did not show any significant effect. The fact that PM_{10} ambient concentrations were only a weak predictor for the corresponding commuters' exposures, may be explained by the different physical properties of PM_{10} in comparison to $PM_{2.5}$. Whereas the latter disperse more uniformly over the urban area, various removal processes act on the first and thus cause stronger spatial variations. Also it is likely that a further undetermined covariate for commuters' exposures to PM_{10} was dust resuspension inside the vehicles in all transport modes – above all when many commuters were on board and moved around inside the vehicles. In addition, the regression coefficient for PM_{10} ambient concentrations is less than half that for $PM_{2.5}$, which may relate with the fact that fine particulates are more closely associated with vehicular sources. The relatively low precision of the particle pumps (see Methods Section) may limit these interpretations.

Finally, wind speed turned out to be negatively associated with commuters' exposure to PM_{10}, which can be attributed to the wind's cleansing effect.

These results are in accordance with results found in previous studies where the determinants of commuters' exposure in transport microenvironments were investigated. A significant association of commuters' exposures to $PM_{2.5}$ with their corresponding concentrations measured at FSM stations has been reported by Adams et al. (2001b) and Kaur et al. (2005b). In turn, Gulliver and Briggs (2004) found a significant association between commuters' exposure to PM_{10} and the respective roadside FSM concentrations. All of these studies found that commuters' exposures were underpredicted by the FSM measurements, by factors of approximately 2, 3 and 1.6, respectively. Kaur et al. (2007) conclude

Table 2
Determinants of commuters' exposures to CO, benzene, $PM_{2.5}$ and PM_{10}

Model	CE	Intercept		FSM		WS		Temperature		Minibus		Bus		R^2	p	n
		b	p	b	p	b	p	b	p	b	p	b	p			
1	CO	4.3	0.000	1.5	0.000	–	–	–	–	9.1	0.000	2.9	0.000	0.636	0.000	117
2	Benz	2.2	0.372	0.8	0.441	–	–	–	–	13.2	0.000	6.0	0.001	0.370	0.000	102
3	$PM_{2.5}$	61.7	0.006	1.9	0.014	–	–	–	–	46.9	0.006	29.5	0.057	0.107	0.002	110
4	PM_{10}	−89.4	0.353	0.8	0.138	−33.7	0.013	19.4	0.003	–	–	–	–	0.099	0.005	97

CE = commuters' exposures, FSM = Fixed site monitoring (CO for model 1 and 2, $PM_{2.5}$ for model 3, and PM_{10} for model 4), WS = wind speed, n = sample size, b = regression coefficient, p = level of significance of coefficients and regression as a whole.

that FSM measurements are relatively poor predictors for commuters' exposure to CO and $PM_{2.5}$ inside vehicles. Negative associations between wind speed and commuters' exposure to particulate matter are described in Adams et al. (2001b) and Gómez-Perales et al. (2004, 2007).

The remaining variability for commuters' exposure concentrations (Models 1–4), and the significant non-zero intercepts of the regression models (Models 1 and 3) must be attributed to other factors not accounted for in the models. For example, a potentially important variable is ventilation, which determines the degree of penetration of external traffic exhaust into the vehicles (Behrentz et al., 2005; Chan et al., 2002). Other determinants that have been reported to impact commuters' exposure are the vehicle age (Duffy and Nelson, 1997), the hour (Gómez-Perales et al., 2004, 2007), the season (Adams et al., 2001a, 2002), the number of intersections and gas stations per kilometer, the driving speed, and the number of vacant lots along the commuting route (Kuo et al., 2000), among others.

3.3. VOC composition

In this section we investigate the possible origin of the measured VOCs, contrasting the penetration of polluted air from outside with potential self-pollution due to outdated engine technology and poor maintenance of the vehicles. For this analysis, we use results from the chemical speciation of VOC samples collected inside the vehicles. As characteristic emissions profiles and ratios have been determined before in Mexico City for various vehicles and other sources (Mugica et al., 2002; Zavala et al., 2006), VOC composition can be used to identify the relative importance of these sources.

Fig. 3a–c shows the relative composition (average with standard deviation) of ten VOCs species for all samples taken inside minibuses, buses and Metrobuses. The similarity in VOC composition inside the three transport modes suggests that there are one or more common external emission sources that penetrate into the respective vehicles in about equal proportions. The high propane fraction (about 50–60%) indicates the presence of LPG combustion, which may originate from LPG-fuelled minibuses or domestic LPG use and leaking pipelines. Extraordinarily high ambient concentrations of compounds associated with LPG in Mexico City have previously been described in Arriaga-Colina et al. (2004), Blake and Rowland (1995) and Gasca et al. (2004). The peaks in acetylene, benzene and toluene are indicative of vehicle exhaust (Mugica et al., 2002; Zavala et al., 2006).

In order to examine the self-pollution of vehicles, we analyzed the toluene/benzene correlations for each vehicle and fuel type, using the slope of the linear regression curve as the indicative ratio between both compounds (scatter plots in Fig. 3a–c). These ratios are similar for minibus (for LPG and gasoline) and diesel buses (1.94 and 1.80, respectively), in spite of different fuels and vehicle technology, and compares well to the ratio of 2.0 reported previously for light duty vehicle exhaust (Zavala et al., 2006). If a significant self-pollution of diesel-fuelled vehicles were to exist, this would have resulted in a different toluene/

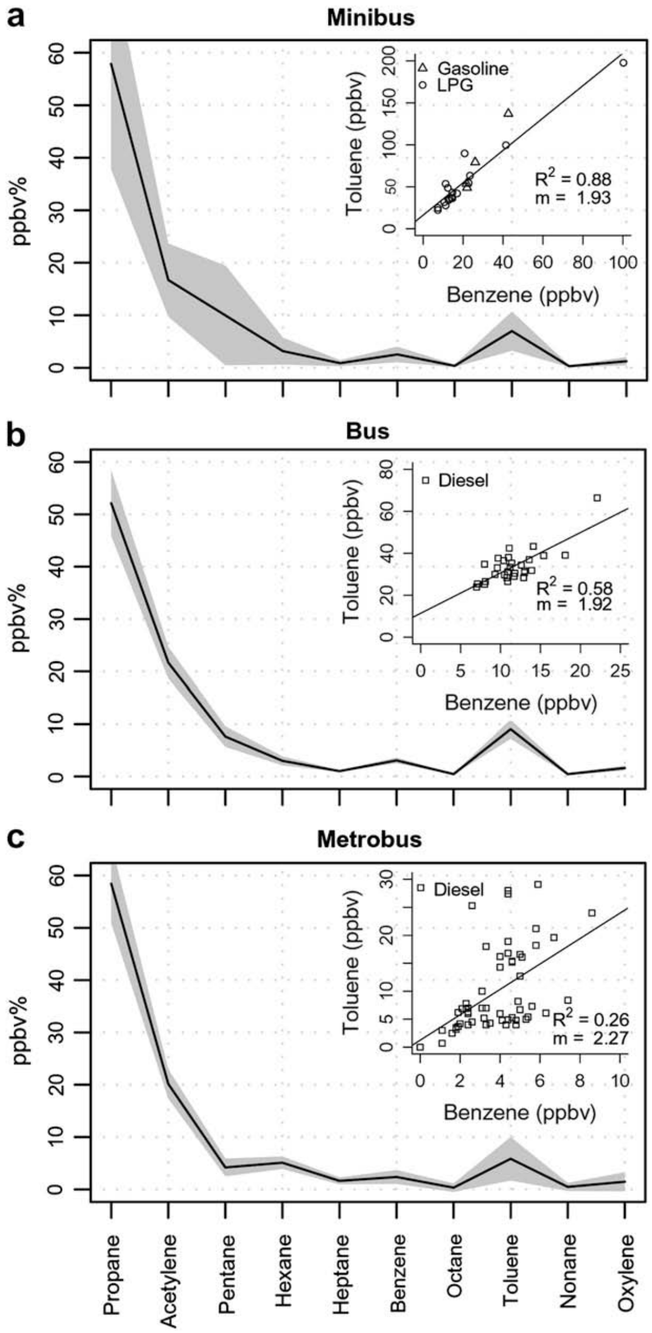

Fig. 3. Average VOC composition (in ppbv%) inside (a) minibuses, (b) buses and (c) Metrobuses. The shaded area indicates the standard deviation. Inserted plots: Toluene/benzene ratios in the three transport modes.

benzene ratio. Mugica et al. (2002) report a value of 4.3, for diesel buses whereas Zavala et al. (2006) indicate a ratio of 1.3. Thus, we conclude that commuters' exposure to transport-related pollutants in the conventional transport modes is mainly due to fresh vehicular emissions penetrating from outside. For Metrobuses, the toluene/benzene ratio is higher (2.27), and with larger variability at lower absolute concentrations of both pollutants. This indicates that in contrast to the conventional transport modes the pollutant mix inside the Metrobus is not dominated by vehicle exhaust from outside, so there is less penetration of air pollution into the cabin of the Metrobus.

An analogous analysis was carried out for the propane/benzene ratio (not shown), used as an indicator of the relative importance of LPG versus gasoline exhaust emissions. We found that ratios do not differ much among gasoline-fuelled minibuses, buses and Metrobuses (14, 12 and 6, respectively), but are significantly smaller than the ratio for LPG-fuelled minibuses (∼40). We conclude that commuters of LPG-fuelled minibuses are exposed to higher levels of LPG associated compounds, due to the high self-pollution of these vehicles. The highest propane concentrations were measured inside the vehicle presenting the maximum CO concentrations previously reported in this paper. Therefore, we further conclude that extreme self-pollution in poorly maintained vehicles can affect commuters' exposure to various air pollutants.

Finally, the fairly constant CO/benzene ratio of about 0.36 ppm/ppb for all modes of transportation supports our conclusion about that the penetration of emissions from surrounding traffic is the primary source of CO inside vehicles. Differences between transport modes may therefore be due to differences in ventilation and air exchange rates, and the fact that Metrobuses do not receive direct emissions from exhaust pipes of gas powered vehicles idling or accelerating right in front of them, a common situation for minibuses and buses that do not have a dedicated lane for themselves.

4. Conclusions

We measured commuters' exposure to CO, VOCs, $PM_{2.5}$ and PM_{10} before and after the implementation of the Metrobus BRT system in Mexico City. The reductions observed after this change in the public transportation system were considerable and significant for CO, benzene, and $PM_{2.5}$, which are pollutants mainly associated with vehicular emissions. For these pollutants, reductions represented on average 45%, 69% and 30% less commuters' exposure, respectively, relative to minibuses, and on average 25%, 54%, and 20% less commuters' exposures, respectively, relative to buses. A chemical composition analysis of VOCs revealed that most of commuters' exposures to these compounds come from surrounding traffic emissions and LPG that penetrate into the vehicle. Self-pollution is also found to be important for LPG-fuelled minibuses, and was extreme in a few cases of poorly maintained vehicles.

From these findings we conclude that commuters' exposures to air pollutants during commuting could be effectively reduced by BRT systems, mainly by reducing the penetration of emissions from surrounding traffic. This result may be due to the optimization of the Metrobuses' ventilation, the height of its intake point, and the distance to surrounding vehicular sources. BRT systems should therefore be considered as a cleaner and less hazardous alternative (from the health point of view) to conventional public transport systems, especially in the quickly growing cities of developing countries. At the same time, a proper maintenance of conventional transport modes should be ensured to reduce commuters' exposures.

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